THE INFLUENCE OF SPECIMEN DESIGN AND TEST PROCEDURE ON RESULTS OF BUCKLING INVESTIGATIONS OF SHELL STRUCTURES

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Key Words

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Buckling

Shell structures

Abstract

The following aspects of buckling tests of shell structures are discussed: (a) the introduction of load into test specimens without causing undue stress concentrations or deformations, (b) the selection of materials for the construction of test specimens, (c) the use of strain gages in providing information essential to understanding specimen behavior, and (d) the feasibility of experimental studies that attempt to demonstrate the lightweight characteristics of shells whose buckling behavior has not been established. In each instance the discussion is exemplified by test results from the literature. Several instances are noted in which the buckling behavior of shells is altered considerably by small changes in specimen design and in which the use of strain gages was helpful in understanding specimen behavior.

Introduction

The quality of data from buckling tests on shell structures is influenced to a considerable degree by specimen design and test procedure. However, information regarding suitable specimen design and satisfactory test procedure is difficult to obtain. Such information, if published at all, is often an aside to the main purpose of the test report (to publish test data), and, as such, is not available to many readers. The purpose of the present paper is to discuss certain aspects of specimen design and test procedure with the aid of recent experience at the NASA Langley Research Center from tests of shell structures in buckling. Much of the information presented is not new; it has appeared in some 20 odd test reports in recent years. The present paper brings together these experiences for discussion.

Discussion of specimen design is centered around the provision of satisfactory end design (boundary conditions) of test specimens and around the desirability of using elastic materials in the construction of specimens. In addition, the importance of reporting all details of construction is noted.

Discussion of test procedure is concerned with determining the structural behavior and buckling strength of shell structures. The help of strain gages in making this determination is indicated.

Finally, the philosophy of multipurpose tests is discussed with the use of recent examples in the literature which clearly illustrate that it is desirable to establish detailed structural behavior of shells as a separate goal rather than to combine this goal in a test program with the additional goal of demonstrating minimum-weight design characteristics of the shells.

Symbols

b	width of plate element
c	fixity coefficient in Euler column equation
D_x, D_y	bending stiffness of corrugated shear web in lengthwise and depthwise direction of web, respectively
E	Young's modulus
h	depth of shear beam

l	length of compression panel
M	applied bending moment on cylinder or beam
p	internal pressure
P	applied force
R	radius of cylinder
t	thickness
x,y	coordinates in lengthwise and depthwise direction
σ	buckling stress
ρ	radius of gyration
λ	half wavelength of buckles
ϵ	strain

Subscripts:

cr	critical or buckling (calculated value)
cy	compressive yield
e	edge
n	new design
o	original design
S	skin
ult	ultimate
W	web of stiffener

Specimen Design

Detailed design of the test specimens discussed herein is generally predicated upon the introduction of load into the test specimens without undue deformations or stress concentrations. Several types of specimens are considered, and examples of the increase in load-carrying capability derived from improved designs are indicated.

Shear load is normally introduced into a shear web through buffer bays (Fig. 1(a)). The buffer bays are either made narrower or are made thicker than the rest of the bays in the shear web in order to inhibit buckling and failure of the web near the location where load is introduced and where heavy members and bolts are used to accommodate the introduction of load.

A recent investigation (1) of the strength of corrugated webs in shear indicates that buffer bays in corrugated webs must be extremely short in order to be effective. Buckle length is proportional to the fourth root of the ratio of the bending stiffness of the corrugated sheet in the lengthwise direction of the web to the bending stiffness in the depthwise direction (see eq. on Fig. 1(a)). Because this ratio is extremely small, the width of the buffer bay must be small compared to the depth of the web in order to prevent buckling of the buffer bay. In one preliminary test of a web with buffer bays that were too wide (approximately one wavelength wide), failure occurred in a buffer bay. For the succeeding test, the width of the buffer bays were cut in half, and failure occurred in the test section of the web rather than in the buffer bays. The narrower buffer bays improved the load-carrying capability of the web by 43 percent (Fig. 1(a)).

In the same test series a preliminary test was made with a corrugated web fastened to the tension and compression flanges by rivets at the crests of each corrugation. (See Fig. 1(b).) This method of attachment leaves the corrugated sheet between crests free and unsupported. In the test of the web, local buckles appeared to emanate from the unsupported sheet and spread throughout the web. For a succeeding test, a narrow doubler strip was bonded to the top and bottom of the web prior to riveting the web to the flanges. The strip supported the otherwise free edges of the web and increased the failing load of the web by 18 percent (Fig. 1(b)).

Conventional Unstiffened Thin-Wall Cylinders

The results of two separate investigations on the buckling strength of conventional unstiffened thin-wall cylinders in bending are given in Fig. 2. The principal difference between the two investigations lies in the end-attachment design of the test cylinders. In the first test series (2), attachment was made directly to heavy end fixtures; whereas, in the second series (3), the test section was separated from the heavy end fixtures by short buffer bays. Curves faired through the lower limit of the test data from the two studies are given in Fig. 2. It will be noted that the addition of the buffer bays improved the load-carrying capability of the test cylinders by as much as 60 percent.

The results of a separate study of the strength of conventional unstiffened thin-wall cylinders in compression are given in Fig. 3. In this study the effect of a weak longitudinal splice on the buckling strength of a test cylinder was investigated. The study was made on unstiffened cylinders in connection with a study of waffle-like cylinders where splices with adequate stiffness are somewhat more difficult to obtain than in unstiffened cylinders.

Tests (unpublished) were made on two cylinders with splices formed from a butt strap 0.040 in. (1.02 mm) thick by 1 in. (2.54 cm) wide; the strap was fastened to the cylinder by two double rows of rivets. Corresponding tests (4) were made on three cylinders with 0.064-inch (1.62-mm) straps. For these tests an adhesive, in addition to rivets, was used in attaching the straps to the cylinder. It will be noted that the improved splice increased the load-carrying capability of the cylinders by 47 percent.

Filament-Wound Glass-Epoxy Cylinders

In compression tests on cylinders of somewhat different construction, it was found necessary to reinforce the ends of the cylinders in order to prevent failure at the ends. Reinforcement for filament-wound glass-epoxy cylinders was satisfactorily achieved by building up the thickness of the wall to approximately double thickness in the vicinity of the ends (5). This reinforcement moved failures from the end of the cylinder, where bearing pressure was somewhat nonuniform because of irregularities in end grind and platen alinement, to the central portion of the specimen and increased the load-carrying capability of the cylinders by as much as 46 percent (Fig. 4).

Honeycomb Sandwich Panels and Cylinders

For honeycomb sandwich panels and cylinders, end reinforcement was satisfactorily achieved with the use of scalloped doublers. This design was first used in tests on sandwich panels (6) which were tested "flat ended" between the platens of a testing machine while supported on the unloaded edges by "knife edge" fixtures (Fig. 5(a)). In preliminary tests without doublers, failure in the form of a crease of short wavelength always occurred at the end of the panel next to the testing machine platen. When short doublers were added to each side of the panel at each end, failure occurred at the end of the doubler. However, when the doubler was made longer and was scalloped, failure occurred in the central portion of the panel.

A similar scallop design was recently used in a series of three tests on honeycomb sandwich cylinders in bending (7). Of the three cylinders tested, two cylinders failed near the ends of the scallops and the other failed in the central portion of the cylinder. The location of failure coincided with the location of maximum wall bending moment of a direction tending to bend the wall inward. The wall bending moments arise during loading from restraint of radial growth of the cylinder by end fixtures. The wall bending moments of a cylinder without doublers vary with distance from the end of the cylinder in a manner as shown by the lower sketch in Fig. 5(b). Evidently the preference of the cylinders to fail inward rather than outward and the length of the scalloped doublers determined the location of failure. For those cylinders which failed at the end of the doubler, the bending stresses at that location were greater than those of the same sign existing elsewhere in the cylinder; that is, the doublers were not long enough to include the greater bending stresses at the end of the doubler. For the cylinder which failed in the central portion of the cylinder, the bending stresses at the failure location were greater than those existing at the end of the doubler.

Flat-End Column Tests - Twisting

A discussion of end design of test specimens for buckling tests would be incomplete without some mention of flat-end wide-column tests. Flat-end column tests are often made with the expectation that the flat ends of the column provide nearly clamped support. Accordingly, a fixity coefficient of 3.75, or there abouts, is sometimes used in reducing flat-end column test data. Two series of tests will be mentioned to indicate that one cannot always expect this result. The first series of tests (8) was made on panels with closely spaced, deep, Z-section stiffeners with a depth-thickness ratio of 30 and with a thickness equal to that of the panel skin. Results of the tests are given in Fig. 6 and compared with calculations made with the help of Ref. (9) and the assumption of simple support. Failure is assumed to be an interaction of column bending and twisting, with twisting predominating in the short panels and column bending predominating in the longer panels. Note that failure of the shorter panels is predicted reasonably well by calculation whereas failure of the longer panels occurred at higher stresses than those calculated on the basis of the simple-support assumption. The number given in parentheses near each test point in Fig. 6 denotes the column fixity coefficient that would be required to bring calculation and test into agreement. It will be noted that the coefficients are considerably less than the coefficients for clamped ends of 4.0 and that they tend toward the clamped value as the stiffening becomes more conventional and as the panels become longer.

It is well known that practical panels develop out-of-plane deflections before ultimate load is reached (10). Such deflections, particularly in short panels with deep stiffeners with a tendency to twist, permit the flat end of the panel to rock on the platen of the testing machine and thus reduce the direct load from the platen to the outstanding flange of the stiffener. Such behavior tends toward a simple-support condition and is believed to account for the low coefficients of fixity associated with the tests of Fig. 6. Some support for this conclusion is depicted in the photograph of a failed test panel of Fig. 7.

Flat-End Column Tests - Plasticity

The second test series was conducted on Z-stiffened panels at the other end of the configuration scale. The panels had shallow widely spaced Z-stiffeners of the same thickness as the panel (11). Some results of the tests are given in Fig. 8 and are compared with a calculation made by the use of the column formula and a fixity coefficient that varied with edge stress in the panel (12). At the lower values of edge stress, good agreement was obtained with tests with the use of a fixity coefficient of 3.75. However, at the higher values of edge stress, a fixity coefficient of unity was needed in order to obtain agreement with tests (see diagram of variation of fixity coefficient with edge stress). This result probably can be explained by the observation that highly stressed columns tend to develop "plastic hinges" near the ends of the column because of the high compressive stresses resulting from the superposition of bending stresses associated with restraint of bending and normal stresses associated with applied load. Accordingly, if the applied load results in edge stresses approaching the compressive yield stress, it is inconceivable that appreciable clamping exists and the effective length of the column will be nearly the actual length as in a simply supported column. Thus, the results of flat-end column tests on highly stressed columns should not be extrapolated to other values of fixity coefficient, as is often done with elastic columns.

Pressurized Cylinders - Plasticity

Another example of test data influenced by plasticity in an unexpected manner is given in Fig. 9. Two curves are given for similar tests on pressurized cylinders in compression. One curve represents the results obtained for Mylar cylinders (13) and is in agreement with similar tests of 7075-T6 aluminum-alloy cylinders (14). The other curve was taken from tests of half-hard 18-8 stainless-steel cylinders (15). The difference between the two sets of data is believed to result from plasticity effects in the stainless-steel cylinders, which were fabricated from material with a rather rounded stress-strain curve. Plasticity effects were aggravated by secondary bending stresses arising from restraint of radial growth at the ends of the cylinders by end rings. Radial growth arises from pressurization stresses and Poisson expansion of the wall of the cylinder during loading. Hence, plasticity effects may occur even though the membrane stresses in the cylinder may be well below the proportional limit of the wall material. These tests and the flat-end column tests just discussed indicate the desirability of using elastic materials in the construction of buckling test specimens if the object of the tests is to obtain general research results rather than to conduct proof tests.

Other Details of Construction

The importance of reporting all known structural and material details in the test report cannot be overemphasized. The test engineer is inclined to report only those details that were used in his analysis of the tests. However, others may be interested in comparing the data with a different set of parameters (parameters which perhaps cannot be obtained from the reported data). Fig. 10 lists some structural details which exemplify this premise. Each of these items were at one time considered to be of insufficient importance to be included in the test report but have since been found to be quite significant.

The effects of riveting details is discussed in Ref. (16) where changes in detail are shown to cause the failing mode of short Z-stiffened compression panels to change from inter-rivet buckling to wrinkling or forced crippling and, finally, to crippling as more and heavier rivets are used in the construction of the panels. The significance of stiffener location is exemplified in Ref. (17) where differences in strength of more than a factor of 2 were obtained between cylinders with stiffeners on the inside surface of the skin and cylinders with stiffeners on the outside surface of the skin. The effects of stiffener shape can be seen from a study of the buckling charts of Ref. (18) where data for buckling of Z-stiffened panels in a combined local and twisting mode are presented. The influence of such items as type of epoxy or glass, volume fraction of glass and epoxy, direction of windings, and number and thickness of windings on the buckling strength of filament-wound glass-epoxy cylinders is discussed in Ref. (5). Many of these details are not included in contemporary test reports. Finally, the contribution of honeycomb cores to the stiffness and load-carrying capacity of sandwich composites is discussed in Ref. (7). In addition, the deleterious effect of core buckling on the composite strength is considered, an effect which can be taken into account only if detailed geometry of the core is known.

Test Procedure

The problem of determining the buckling load of a shell structure is not always a straightforward one, and many times test engineers find that the test data are inadequate to make this determination satisfactorily. Proper instrumentation can be of assistance, and this section of the paper briefly discusses three separate buckling tests in which strain-gage instrumentation was useful in determining the buckling behavior of shell structures.

A definition of the "strain-reversal buckling load" of shell structures (19) will be helpful in the discussion. This load is defined in Fig. 11 where it is seen to be the load at which the strain on one side of the wall in the vicinity of a developing buckle stops increasing with load and starts decreasing. The strain-reversal method of determining the buckling load was first applied to flat-plate structures but is sometimes used in tests of curved shells as well. Its use generally predicts loads at which out-of-plane (buckle-like) deformations begin to grow rapidly with small increases in applied load.

Strain Reversal - Pressurized Cylinders

The significance of the strain-reversal load in determining the buckling behavior of pressurized cylinders in bending is illustrated in Fig. 12 where bending moment is plotted against a pressure parameter for a conventional ring-stiffened cylinder. The calculated strain-reversal load (20) is in reasonable agreement with the strain-reversal load as measured with strain gages (14), indicating that the behavior of the cylinder is reasonably well understood. In addition, the strain-reversal load is roughly equal to the calculated buckling load, but the observed behavior of the cylinders at this load did not suggest buckling. The first real outward evidence of buckling occurred at the loads corresponding to the square symbols, that is, the load at which deep diamond-shape buckles suddenly developed.

The strain-gage instrumentation in this test provided the necessary information for understanding the complex behavior of this cylinder. The instrumentation indicates that a "buckling load" corresponding to the calculated buckling load was actually passed through prior to buckling of the cylinder into the diamond-shape buckle pattern. Without the strain-gage information, this behavior may not have been evident.

Panel Buckling - Corrugated Cylinder

Strain-gage instrumentation was helpful in another recent test, that of a corrugated ring-stiffened cylinder subjected to bending (21); the information obtained from strain gages indicated the presence of a mode of buckling that might have been overlooked without the strain-gage data. Results of the test are shown in Fig. 13, where the moment on the cylinder is plotted as a function of strain as measured by gages located on the generator of the cylinder corresponding to the extreme compression fiber. Strain reversal is indicated at a load of approximately 75 percent of the load at which failure ultimately occurred. The strain-gage data at this load indicates that the wall of the cylinder was "buckled" in at gage location 1, out at gage location 2, in at gage location 3, and out at gage location 4, corresponding to buckling into a panel instability mode - that is, buckling between rings. Strain reversal in this case occurred near the calculated load for panel instability. Upon further loading, the panel instability buckles grew with load until, at approximately 95 percent of the failing load, the cylinder wall snapped from the panel-instability mode to a general-instability mode entailing buckling of the corrugated wall and rings as a composite wall. The strain-gage data clearly indicate the presence of the panel-instability mode which may not have been evident without the data.

Truss-Core Sandwich Cylinder

Figure 14 illustrates a somewhat different use of strain-gage information in a buckling test (22). The test specimen was a 10-foot-diameter truss-core sandwich cylinder of all-welded construction. Weld shrinkage during fabrication caused imperfections which were in isolated instances about 1/2 as deep as the wall thickness. The region of highest compressive stress was instrumented with strain gages prior to testing. The load-strain plots of Fig. 14 show typical results from strain gages; the pair of curves on the right is from gages near the most severe imperfection, the other curves are from gages in more typical areas of the cylinder. It will be noted that the severe imperfection started to grow from the beginning of load application as evidenced by the separation of the curves of the inside and outside gages. At failure one of the gages experienced strain reversal. Load on the cylinder at failure was 62 percent of the calculated small-deflection buckling load. It is believed that the strain-gage information in this instance offers an explanation for the buckling behavior of the cylinder in that the monitored imperfection evidently influenced the location at which buckles developed and perhaps also influenced the load level at which failure occurred.

Multipurpose Tests

This section of the paper cites two recent test series which indicate that broad-scope studies of structural behavior often prove little if undertaken before important details of structural behavior have been established. The two studies were made to demonstrate the light-weight or efficiency characteristics of advanced structural configurations whose buckling behavior had not been studied experimentally.

The first study (23) was conducted on truss-core sandwich cylinders in compression (Fig. 15(a)). The cylinders were proportioned so that local buckling of the wall would occur at the same load as general instability of the cylinder, a premise often employed in the design of minimum-weight structures. The Euler column load of the wall, treated as a flat plate, was used to predict general instability buckling. In the tests, the cylinders buckled locally and failed soon thereafter in a general instability mode. The tests proved little regarding the load-carrying capability of minimum-weight design truss-core sandwich cylinders, the goal of the test program. Truss-core sandwich cylinders can support loads much greater than the corresponding wide column, if they are not designed to buckle locally at the wide column load. However, the general instability buckling load of truss-core sandwich cylinders had not been established with any degree of reliability, and the experimental study of minimum-weight cylinders was somewhat premature.

In another study (24), minimum-weight design box beams were tested in bending (Fig. 15(b)). Many of the beams were of advanced design employing the use of corrugated webs and honeycomb sandwich plates, beams for which modes of failure had not been established. Of the 14 test beams of the investigation, seven failed at loads less than 50 percent of the design load, one as low as 10 percent. Only five of the beams took more than 62 percent of the design load. The construction of these five beams was more or less conventional, and test results, of at least limited scope, on their buckling behavior is reported in the literature. The test program of Ref. (24)

proved little regarding the design of minimum-weight beams of advanced design because the program was undertaken before detailed beam behavior had been established.

Concluding Remarks

The influence of various aspects of buckling tests of shell structures has been discussed. It is shown (1) that detail design has a considerable influence on the buckling behavior of shells, (2) that small changes in design can result in large changes in buckling strength, (3) that strain gages may be a useful tool for determining shell behavior under load, and (4) that test programs which have objectives that are too broad for the state of the art and the size of the test program are unlikely to produce fruitful results.

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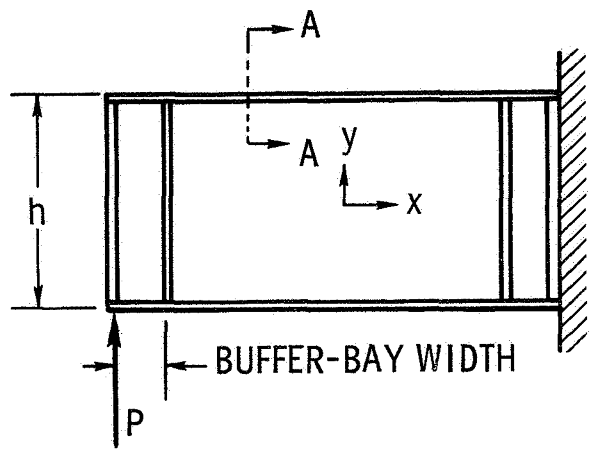
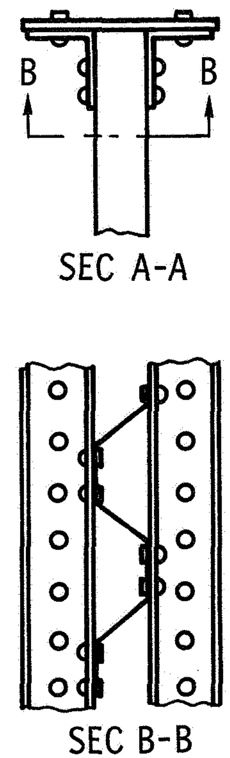


$$\frac{\lambda}{h} \approx \sqrt[4]{\frac{D_x}{D_y}}$$

$$\frac{P_n}{P_o} = 1.43$$

(a) Buffer-bay study.



$$\frac{P_n}{P_o} = 1.18$$

(b) Unsupported-edge study.

Figure 1.- Corrugated shear webs (ref. 1).

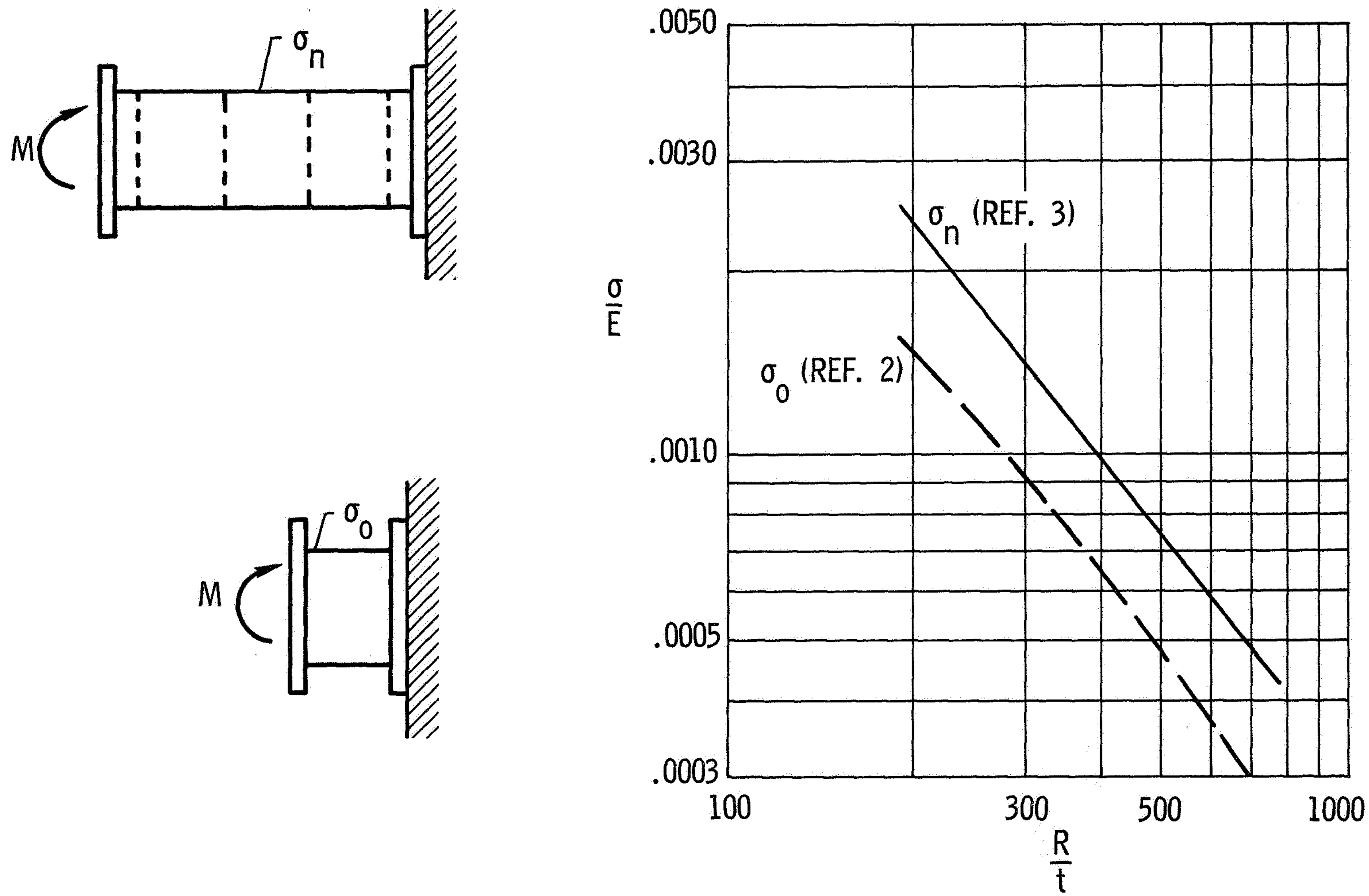
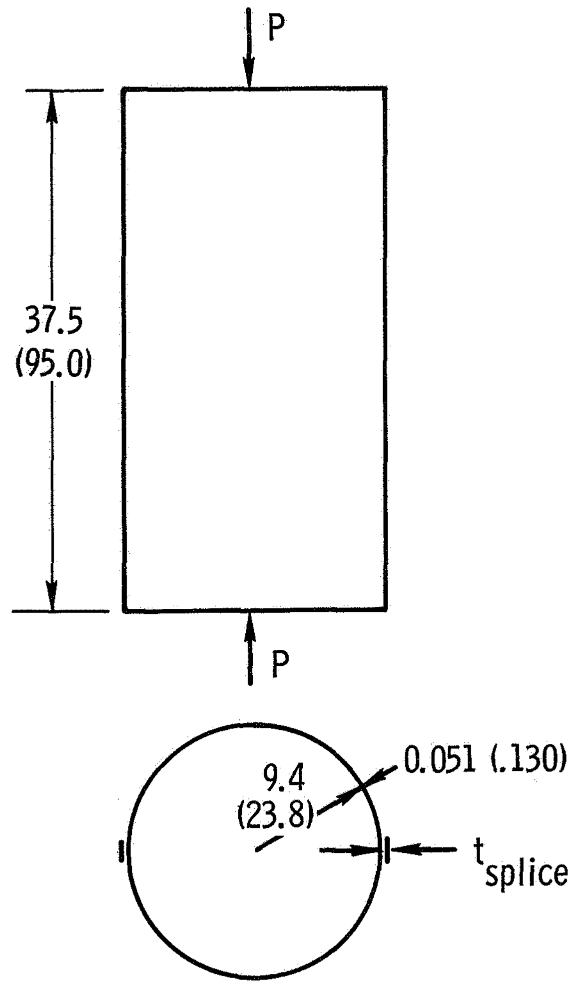


Figure 2.- Conventional unstiffened cylinders in bending.



t_{splice}, in. (cm)	σ, ksi $\left(MN/m^2\right)$	
0.040 (0.102)	18.4 (126)	19.2 (132)
	20.0 (137)	
.064 (.162)	27.1 (186)	28.2 (194)
	28.9 (198)	
	28.5 (196)	

$$\frac{\sigma_n}{\sigma_o} = \frac{28.2}{19.2} = \frac{194}{132} = 1.47$$

Figure 3.- Splices in compression cylinders. Linear dimensions are in inches (cm).

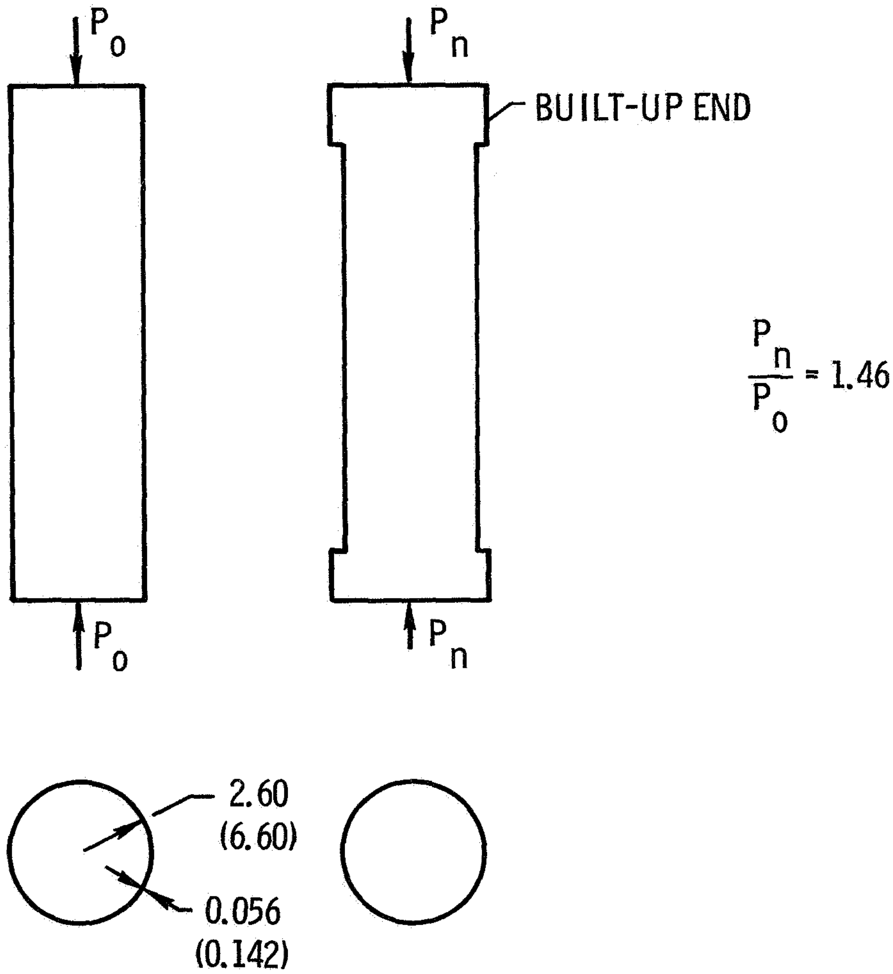
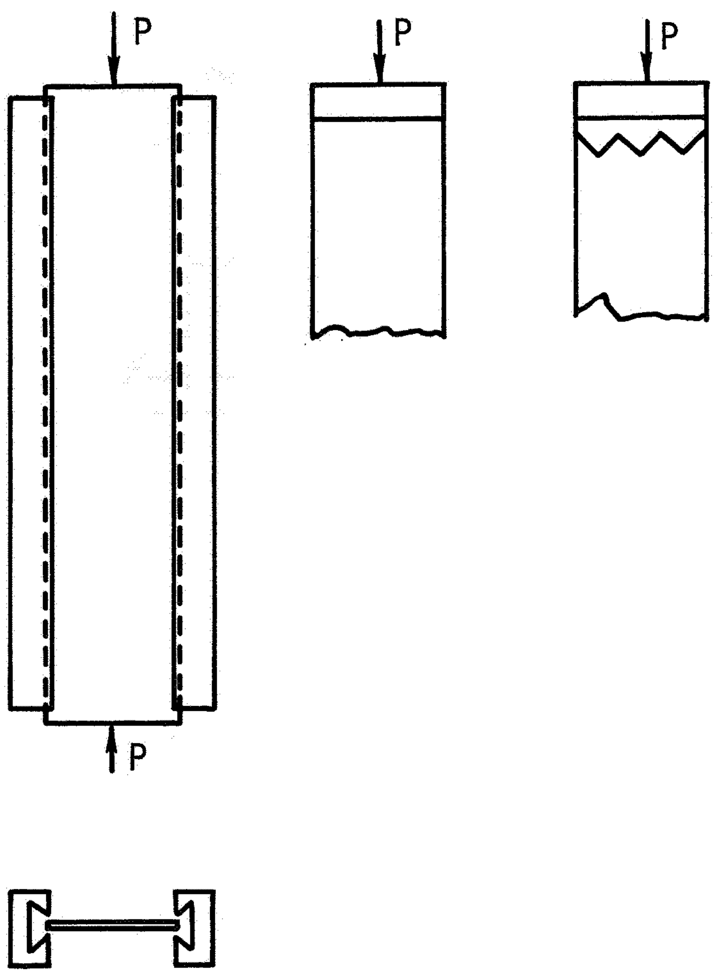
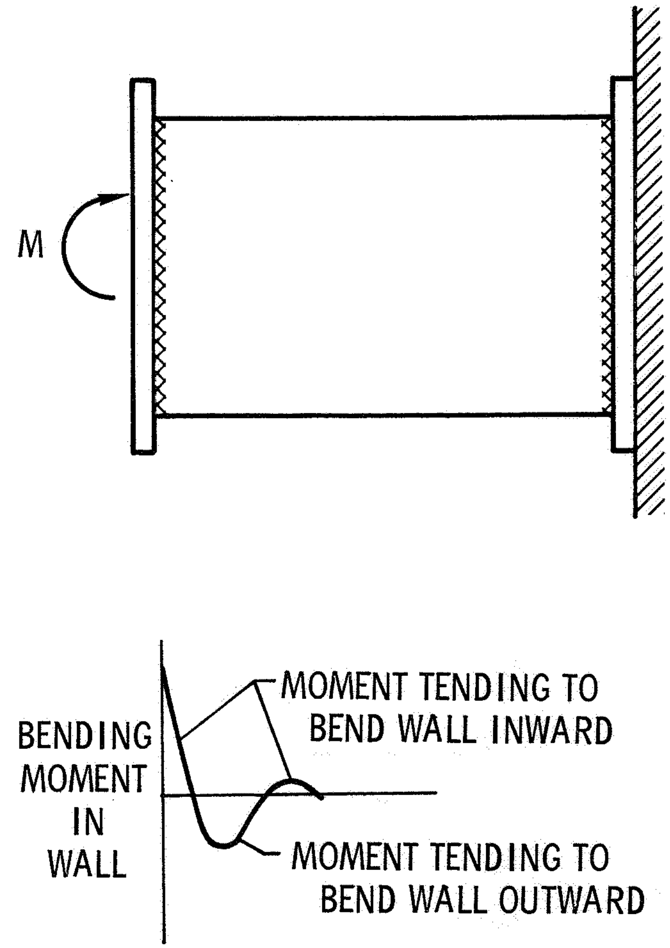


Figure 4.- Filament-wound glass-epoxy cylinders (ref. 5). Linear dimensions are in inches (cm).



(a) Panels (ref. 6).



(b) Cylinders (ref. 7).

Figure 5.- Honeycomb panels and cylinders.

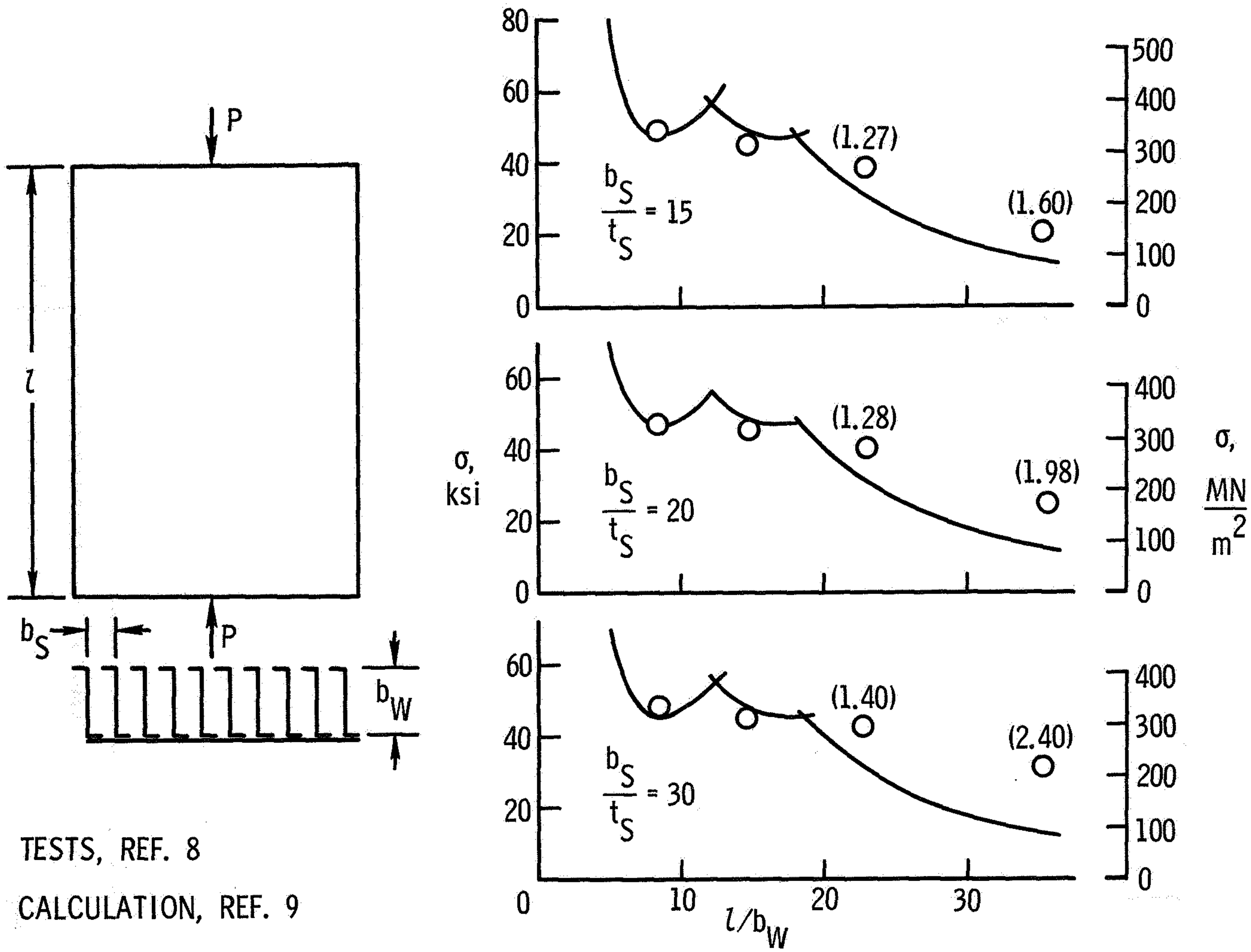


Figure 6.- Flat-end column tests - twisting.

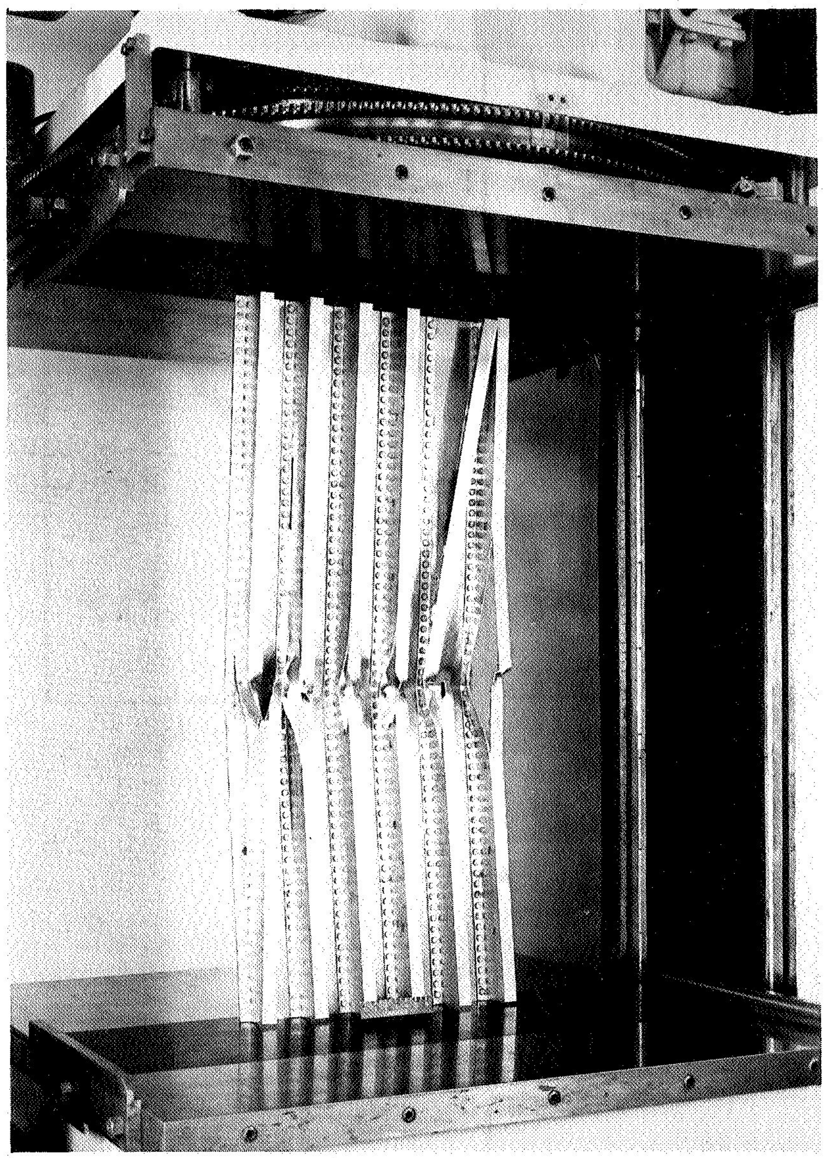


Figure 7.- Failure of test panel.

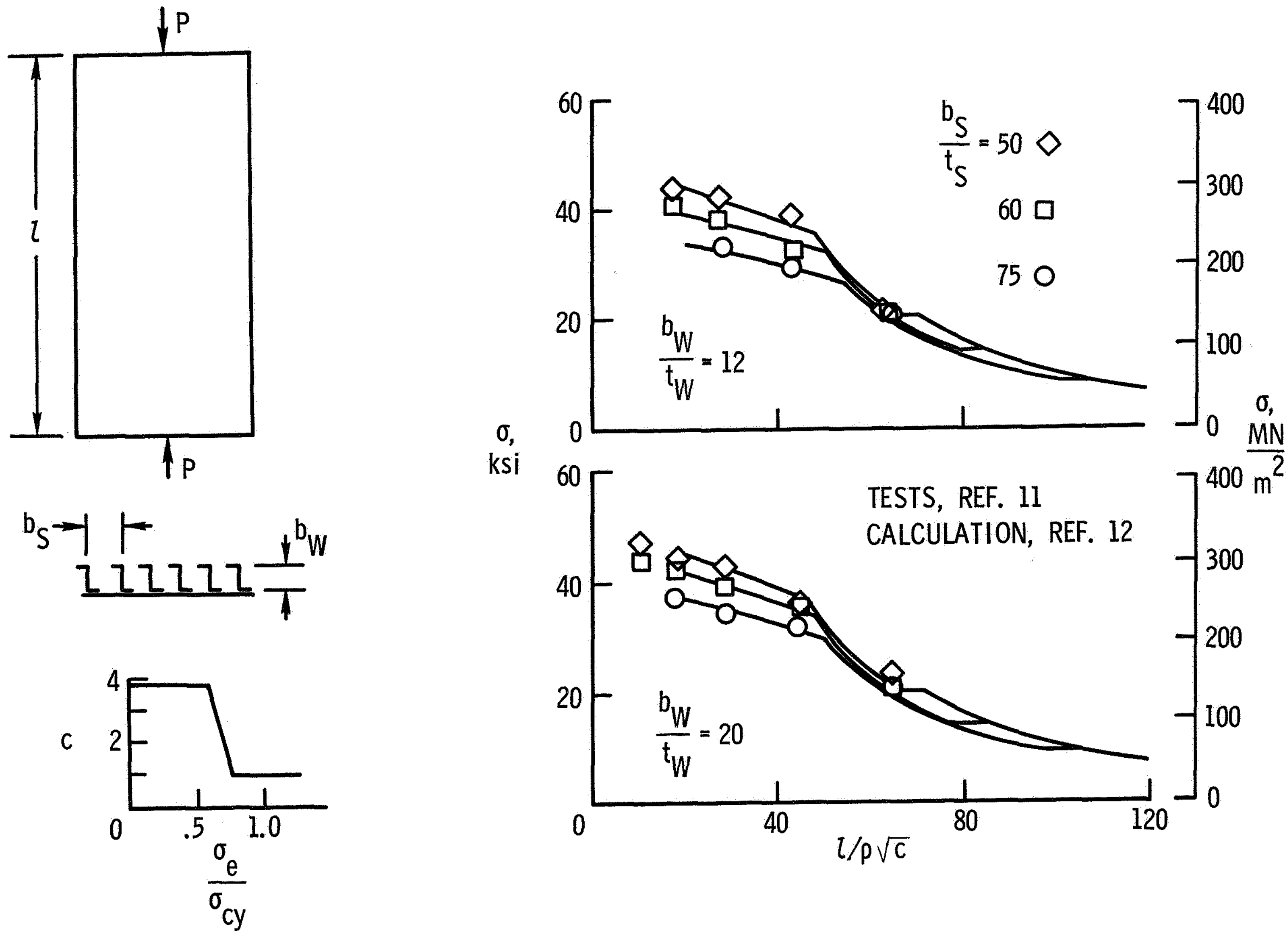


Figure 8.- Flat-end column tests - plasticity.

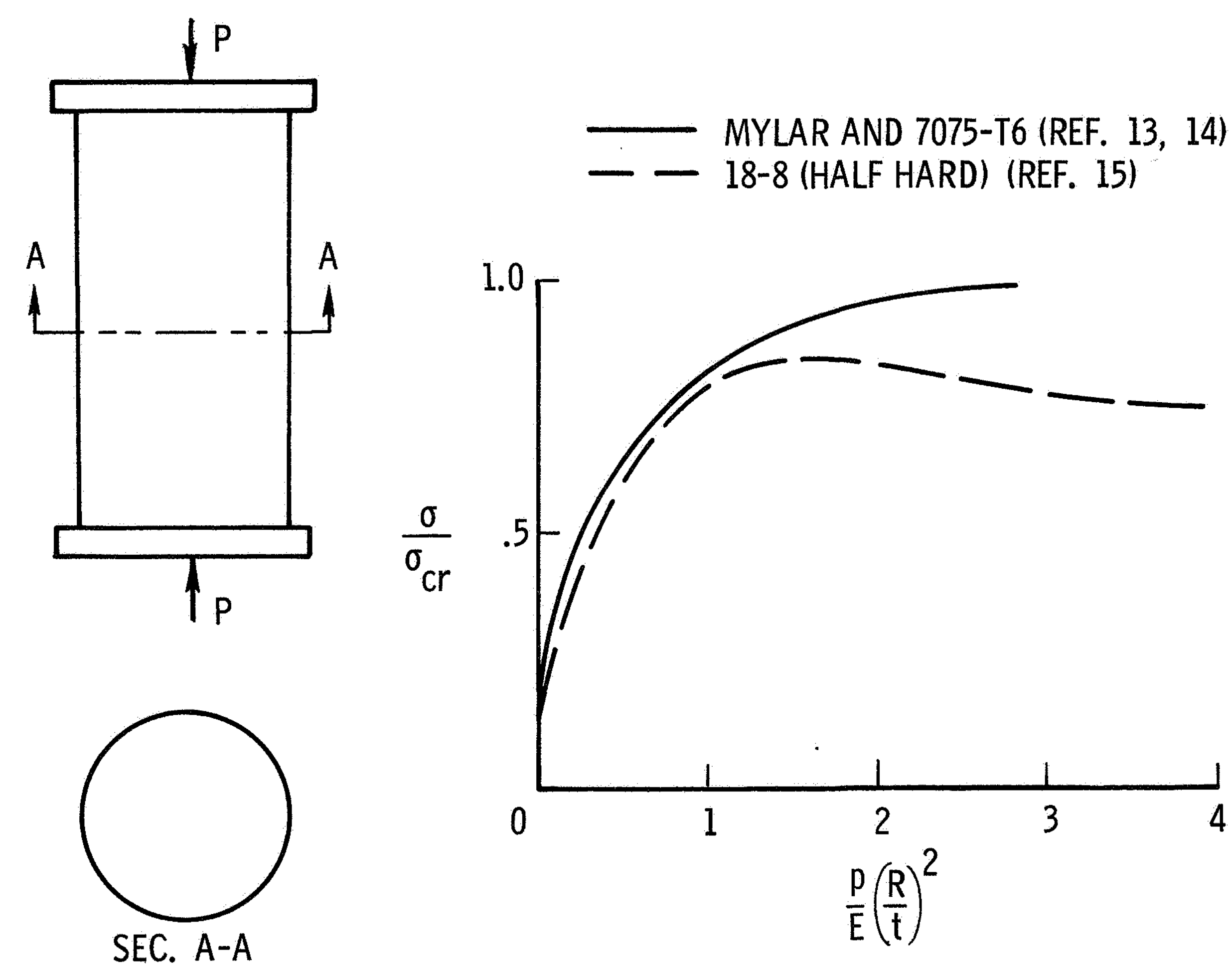


Figure 9.- Buckling of pressurized cylinders - plasticity.

1. RIVET SPACING, OFFSET (REF. 16)
2. INSIDE VS OUTSIDE STIFFENING (REF. 17)
3. STIFFENER SHAPE (REF. 18)
4. COMPOSITION OF GLASS-EPOXY COMPOSITES (REF. 5)
5. CORE DETAILS, HONEYCOMB STRUCTURES (REF. 7)

Figure 10.- Other details of construction.

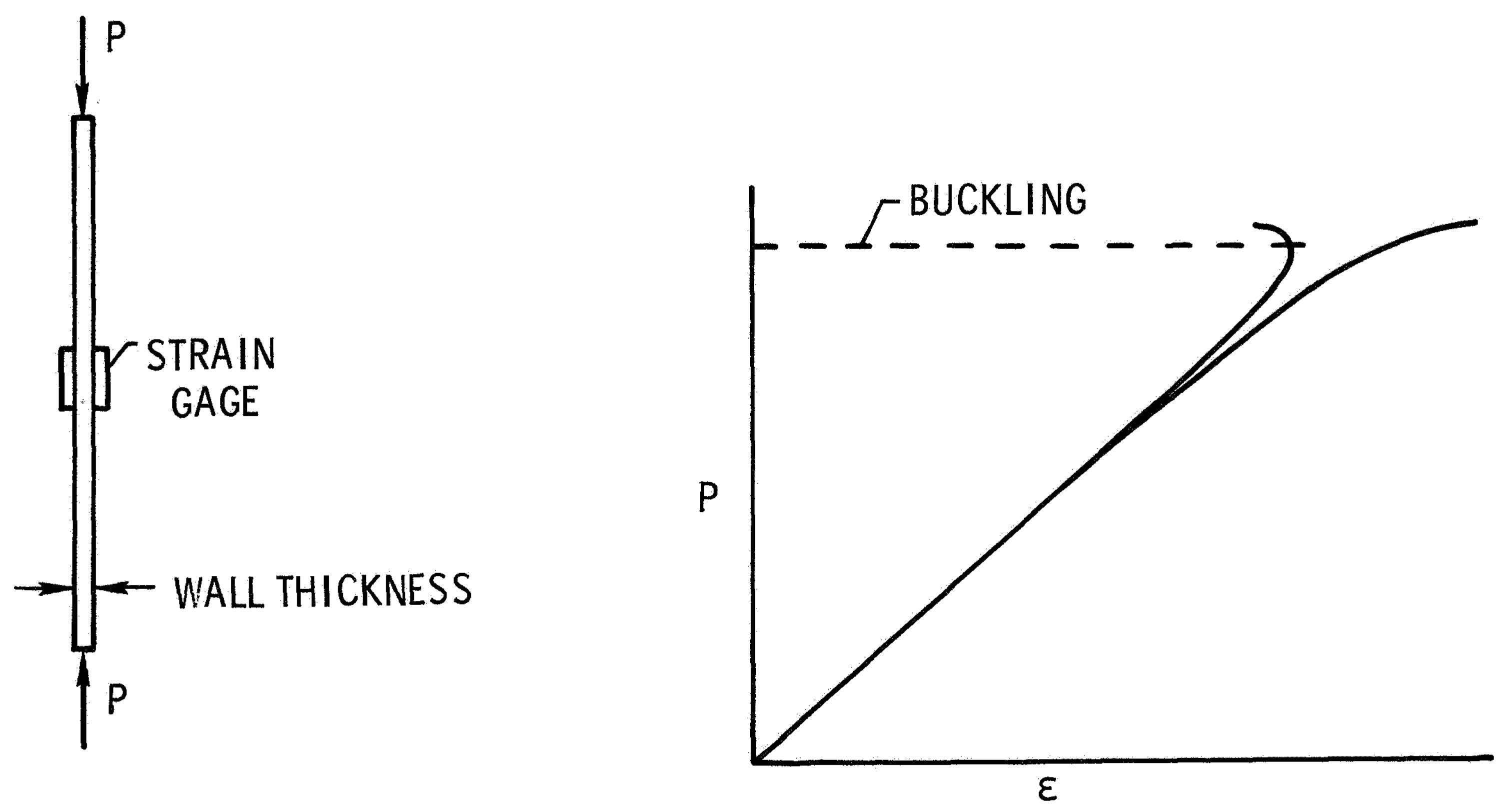


Figure 11.- Strain-reversal buckling load (ref. 19).

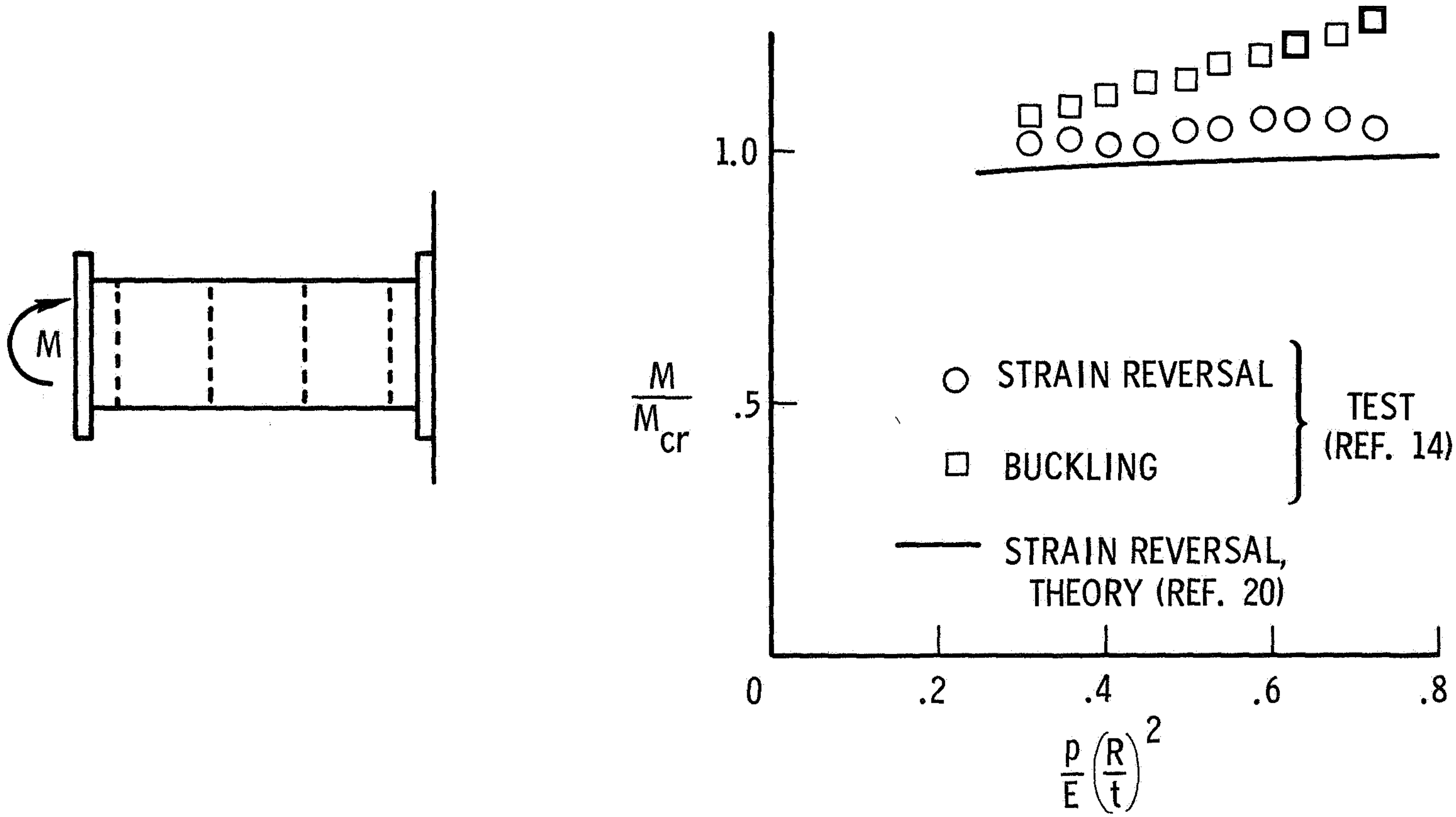


Figure 12.- Strain reversal in pressurized cylinders.

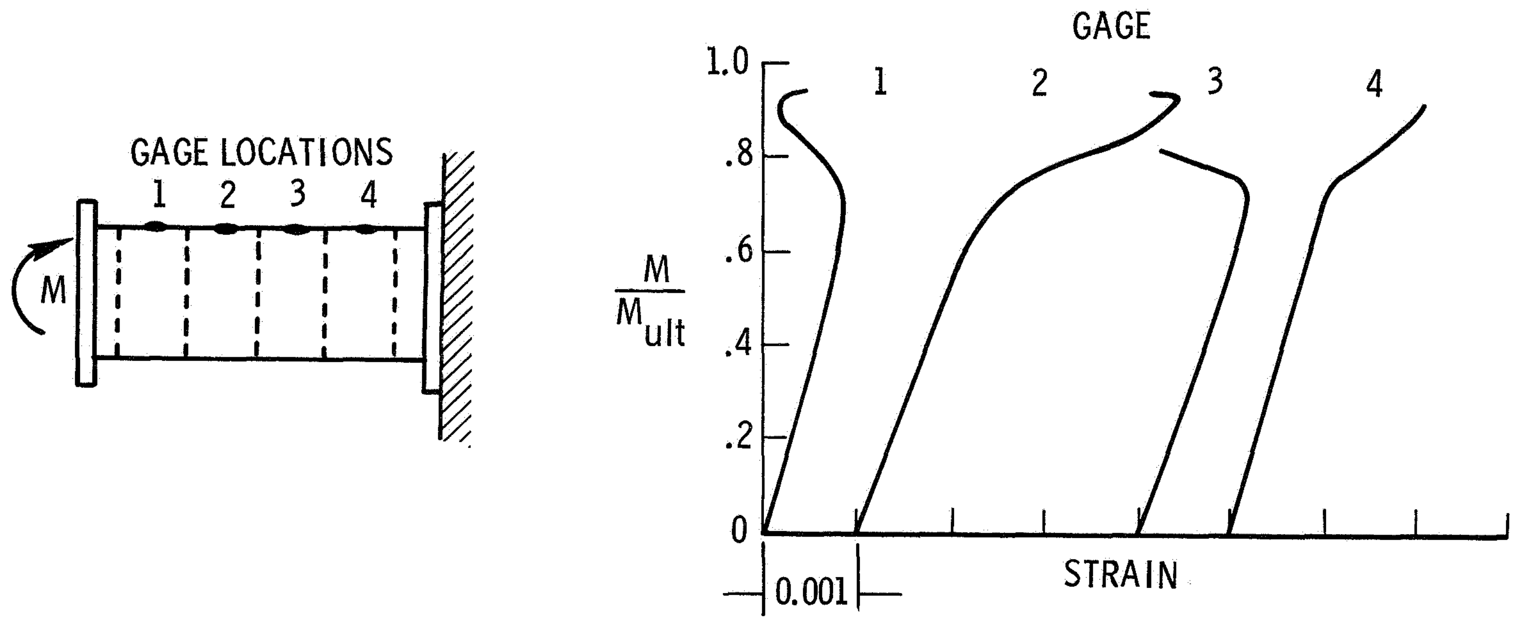


Figure 13.- Panel buckling - corrugated cylinder (ref. 21).

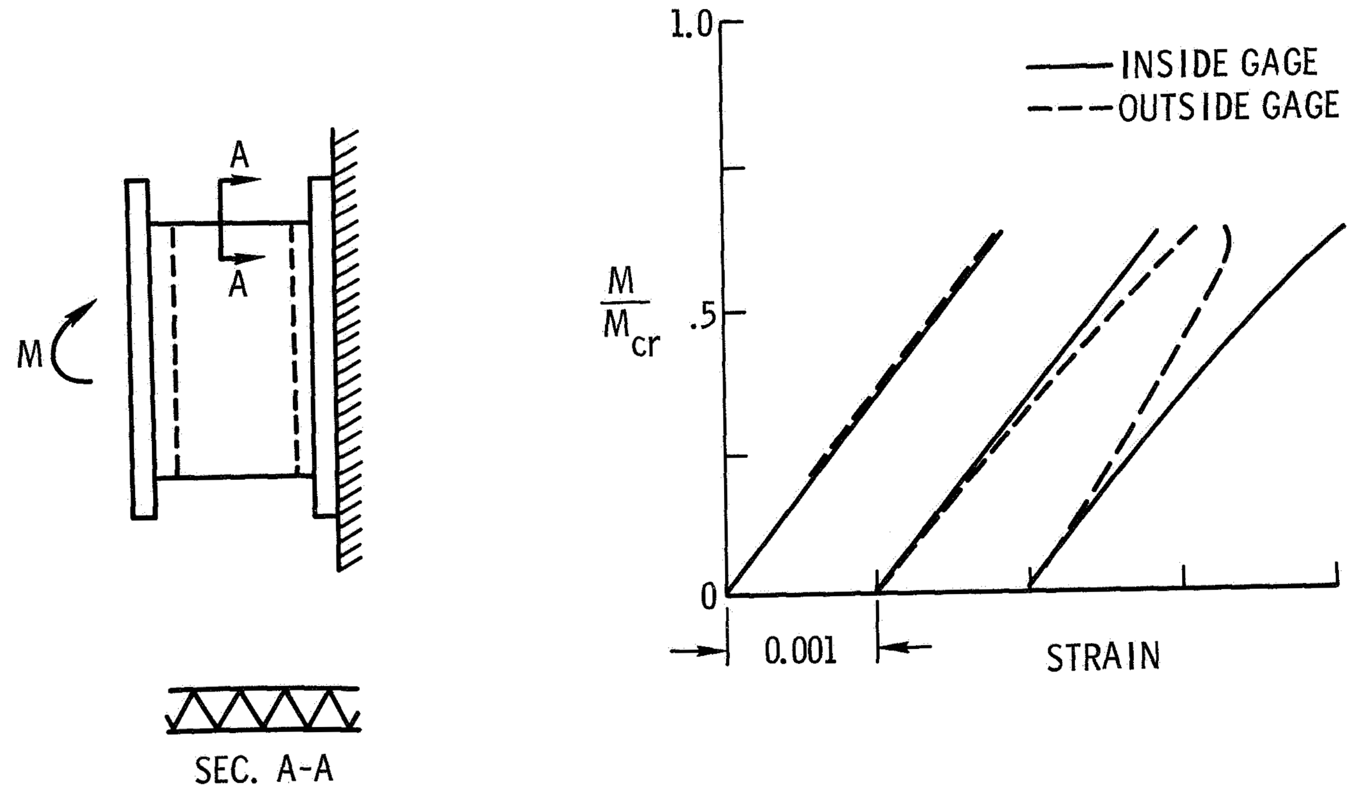
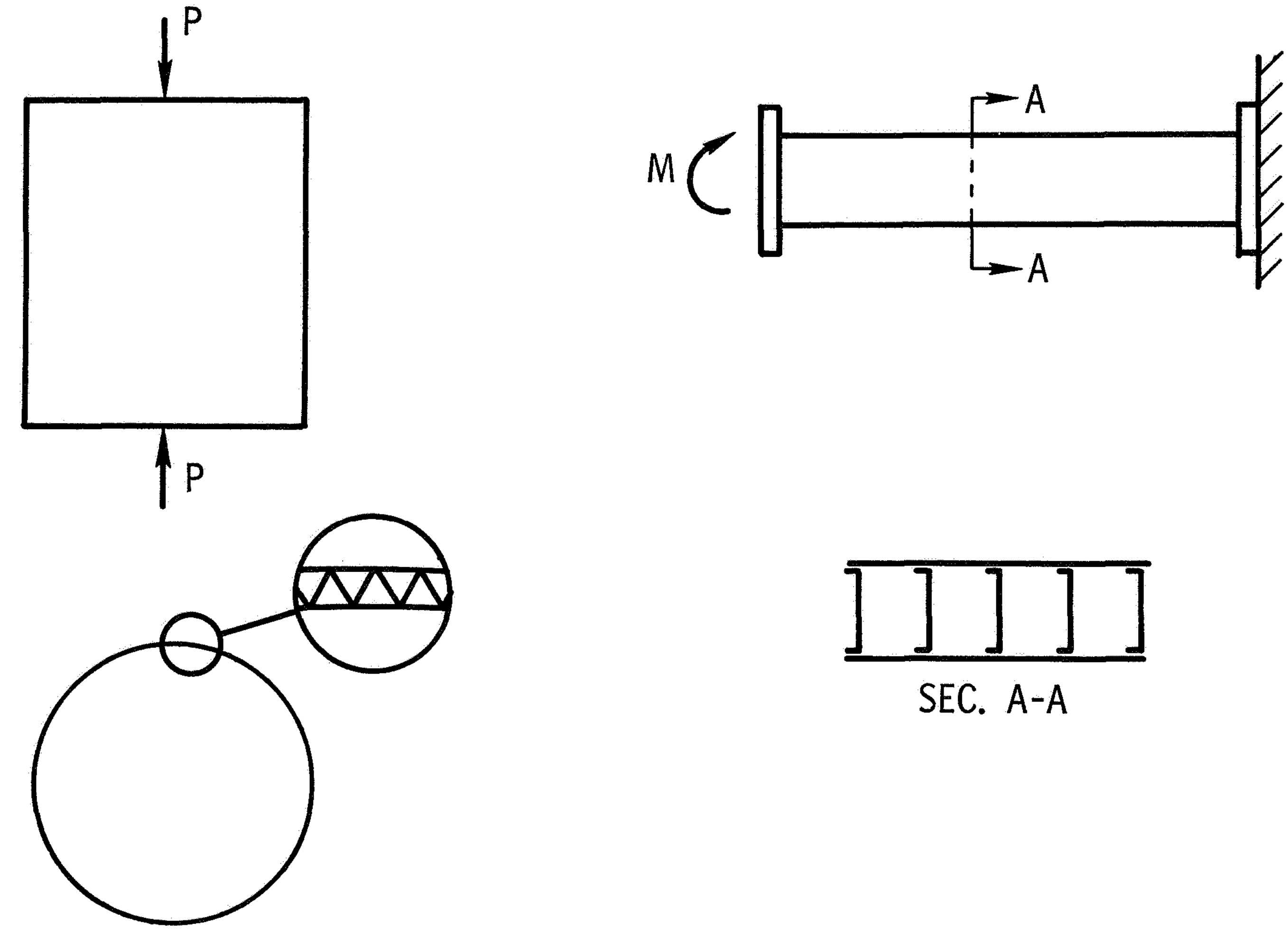


Figure 14.- Buckling of truss-core sandwich cylinder (ref. 22).



(a) Truss-core sandwich cylinders (ref. 23). (b) Multiweb beams (ref. 24).

Figure 15.- Multipurpose tests.

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